Inlet Mode Transition Screening Test for a Turbine-Based Combined-Cycle Propulsion System*

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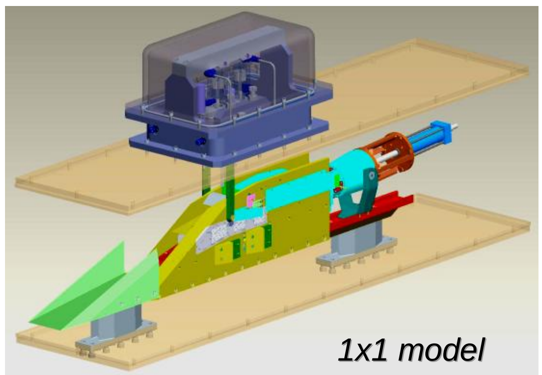

ABSTRACT

A combined computational and experimental study of inlet mode transition needed for Turbine-Based Combined-Cycle (TBCC) propulsion has been conducted. The Inlet Mode Transition Experiment (IMX) model used in this study is based on a careful design of an inlet system that supplies both a turbine engine and a ram/scramjet flowpath in an 'over/under' configuration. Traditional aerodynamic design techniques were used to develop an TBCC inlet design that balances aerodynamic and mechanical constraints to provide a practical approach to inlet mode transition. The current IMX inlet was designed for Mach 7 scramjet operation with an over/under turbine that becomes cocooned beyond its design point at Mach 4. Conceptually, this propulsion system was designed for the needs of the first stage of a two-stage to orbit vehicle. The IMX dual or split-flow inlet matches engine requirements while maintaining both high performance and stability. To verify the design, the small-scale screening experiment was conducted in the NASA GRC 1'x1' Supersonic Wind Tunnel to characterize the performance and operability of this TBCC inlet. In addition, a series of increasing fidelity CFD-based tools were used to analyze the inlet configuration. Both the experiment and CFD analyses indicated that high performance (near MIL-E-5008B recovery) and smooth mode transitions are achievable for this design. The efforts have validated the IMX design and contributed to a large-scale inlet/propulsion test being planned. This large-scale effort will provide the basis for a 'Combined Cycle Engine Testbed', which will be able to address integrated propulsion system and controls technology objectives.

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NOMENCLATURE

Acronyms

AIP	- Aerodynamic Interface Plane
AOA	- Angle Of Attack
CCET	- Combined Cycle Engine Testbed
CFD	- Computational Fluid Dynamics
DMRJ	- Dual Mode RamJet
DMR/SJ	- Dual Mode Ramjet / ScramJet
ESP	- Electronically Scanned Pressures
GRC	- Glenn Research Center
FALCON	- Force Application and Launch from CONtinental United States
HiSTED	- High-Speed Turbine Engine Demonstrator
HS	- High-speed, (refers to scramjet inlet)
IMX	- Inlet Mode transition eXperiment
LIMX	- Large-scale Inlet Mode transition eXperiment
LS	- Low-speed, (refers to turbine engine inlet)
LVDT	- Linear Variable Displacement Transducer
NRA	- NASA Research Announcement
RANS	- Reynolds-Averaged Navier-Stokes (equations)
RATTLRS	- Revolutionary Approach To Turbine-based Long-Range Strike
RTA	- Revolutionary Turbine Accelerator
RTV	- Room Temperature Vulcanizing
VAATE	- Versatile Advanced Affordable Turbine Engine
TBCC	- Turbine-Based Combined-Cycle
vgs	- Vortex Generators
VGC	- Variable Geometry Cowl
VGR	- Variable Geometry Ramp
1D, 2D, 3D	- One, two and three dimensional, respectively

Symbols

C1, C2	- cowl bleed regions 1 and 2
D2	- distortion index, (max-min)/average engine face pressure
H	- height of high-speed cowl
m	- mass flow, (pound-mass/second)
M	- Mach number
p	- static pressure
P	- pressure
Q	- dynamic pressure = $\gamma/2P_sM^2$, (psf – pounds per square foot)
R1-R4	- ramp bleed regions 1 to 4
SW1-SW3	- side wall bleed regions 1 to 3
T	- temperature
x	- axial length
γ	- gamma, ratio of specific heats

Subscripts

hs	- high speed inlet
ls	- low speed inlet
inf	- freestream conditions
o	- freestream conditions
t	- total (stagnation) flow conditions
2	- engine face conditions

INTRODUCTION

High-speed inlet research has effectively split into separate disciplines over the past thirty years. The split occurred to address the airflow requirements of two very different engine systems: the turbojet and the ram/scramjet. However, the relevant flow physics are largely similar between inlets designed for turbine and ram/scram engines. Nomenclature and design approaches have developed divergent paths, as is typical as disciplines mature. The differences have become evident in a project to develop a realistic turbine-based combined cycle (TBCC) engine. This propulsion system uses a turbine engine to boost an accelerating vehicle from takeoff to Mach 4 conditions. Then a dual-mode ram/scramjet (DMR/SJ) further accelerates the vehicle from the transition Mach number to the maximum Mach number, typically around Mach 7. The procedure to switch between the two engines is termed mode transition which occurs at a transition Mach number. The term “inlet mode transition” refers to the closing of the inlet flowpath to the turbine while establishing the design flowpath to the ram/scramjet. The focus of this study is inlet mode transition.

To further introduce the subject of inlet mode transition, it is useful to examine the aerodynamic similarities and differences between inlets designed for either of the two engines. Once an aircraft accelerates past sonic speed, compressibility is no longer just a correction to aerodynamics; it becomes the dominating flow feature. Compressibility is particularly dominant in inlet design because, at supersonic speeds, the inlet is no longer a simple aperture to be sized properly for the engine flow demand. A typical supersonic inlet system must have carefully designed aerodynamic contours and bleed/bypass zones to control shock wave/boundary layer interactions and engine flow demand changes. A TBCC supersonic inlet design must include additional features to split and match the flow for each engine's proper entrance Mach number. The most dominant design feature is variable geometry not only to split the flow, but also to create aerodynamics conducive to high performance. The design of an inlet system capable of TBCC mode transition and high performance presents a difficult challenge that involves integration of past experience, careful application of aerodynamic principles, and high-quality experimental and CFD procedures.

Because the IMX efforts are still underway, detailed reporting of test results and comparisons between test data and the CFD analyses are not discussed in this paper. Instead, the focus will be on the IMX design, pre-test CFD analyses with a high-level overview of the screening experimental results.

This paper discusses the current TBCC inlet research effort in terms of five topics: background & objectives, inlet design approach, small-scale screening experiment, CFD support analyses and overview of screening results. The effort is collectively called Inlet Mode Transition (IMX) research. Background on supersonic, hypersonic and initial mode transition inlet research coupled with the specific objectives of the current effort has led to the IMX design approach. An overview of this approach is then described to introduce the salient features of the IMX design. To validate the design, both a small-scale screening experiment and a set of CFD analyses were conducted. The data from the screening experiment characterized the performance and operability of this TBCC inlet. This small-scale inlet experiment was conducted in the GRC 1'x1' Supersonic Wind Tunnel (SWT). A series of increasing fidelity CFD-based tools was used throughout the effort to provide confidence in the design and provide guidance for test planning and data analysis. Next, the paper outlines the results of the screening experiment that address the objective of operating through a smooth mode transition sequence while maintaining expected low-speed inlet performance and stability. These results provide confidence in the IMX dual-flow inlet design process. As a consequence, the design was selected to be scaled up for a large-scale inlet/propulsion test that is planned to be conducted in the GRC 10'x10' SWT. This large-scale research effort is the basis for a Combined Cycle Engine Testbed (CCET) which will be capable of addressing a wide range of issues critical for mode transitioning propulsion system and controls technology.

BACKGROUND & OBJECTIVES

Over the past three decades, limited progress has been made towards research and development of split flow inlets for multiple flowpaths typical of combined cycle propulsion. One of the earlier efforts that progressed beyond paper studies was an inlet for a Mach 5 reconnaissance aircraft[1,2]. That aircraft differs significantly from current efforts, but the inlet concepts are remarkably similar. For the Mach 5 inlet, performance was identified as one of the greatest uncertainties and motivated a ground test program[3] that was concluded in the early 1990's. The focus of this design and testing effort was to understand performance and bleed system trades for this high Mach number mixed-compression inlet. Specifically, the test quantified performance and operability for the Mach 5 ramjet inlet of the over-under turbojet/ramjet propulsion system. The Mach 5 inlet study was followed by several efforts directed toward dual-flow inlet design and test. Unfortunately, these efforts did not proceed beyond preliminary design and CFD analysis. Based on this knowledge, studies[4-7] began in the late 1990's to develop an inlet for a TBCC concept. This concept was eventually chosen for an X-43B research vehicle development program. However, the X-43B program was not completed due to shifting national priorities. Most recently, hypersonic research focused on TBCC concepts has continued with the HiSTED, Robust Scramjet, RATTLRS and FALCON projects[8-11].

What many of these efforts share is an 'over-under' propulsion system architecture that is fed by a split-flow, variable geometry inlet. The near-term goal of the current effort is to explore how a split-flow inlet can be designed and used to demonstrate that smooth inlet mode transitioning is possible between the two flowpaths. Mode transition for TBCC propulsion has many elements with the inlet aspect characterized by flow balance, flow quality, and operability. Another major goal of the current effort involves the documentation of a design database that encompasses acceptable levels of these inlet characteristics. Both published[12-15] and unpublished studies conducted for TBCC based aircraft suggest that high inlet performance is required or at least expected. Typically, high performance is defined by the military specification for total pressure recovery, MIL-E-5008B. While the desire is to develop an inlet with little to no bleed, a complex inlet system with a sophisticated bleed system is required to obtain these high total pressure recoveries. The long-term goal of the current research effort is to greatly improve the inlet community's confidence to design TBCC inlets for mode transition through the use of validated CFD analysis and design tools.

To address these objectives, the current effort has pursued a two-phase experimental approach: a small-scale screening experiment followed by a large-scale inlet/propulsion system test. For the first phase, a small wind tunnel inlet test model was designed, built and tested in the NASA GRC 1'x1' SWT; this effort is termed the Inlet Mode transition experiment. Due to tunnel size constraints, this small-scale model could not be fully instrumented nor have complete variable geometry features. Instead, the goal was to provide a basis to screen or indicate the merit of the design concept. With initial encouraging results, the second phase of the experiment has begun. A large-scale propulsion research test is now under development to provide higher fidelity measurements than the small-scale IMX experiment. In addition, this large-scale Combine Cycle Engine Testbed will further developed into a true propulsion test rig that can be used to perform integrated systems tests with one or both engines. Integrated inlet/engine systems testing will answer the mode transition questions that exist beyond the inlet functionality.

For the small-scale IMX tests, the primary objectives were to screen an inlet design to demonstrate that high performance and operability were possible and compatible with the variable geometry needed for split flow inlet mode transition. In addition, an important secondary objective was to validate CFD tools that can predict the performance and operability for each inlet, individually, and as a split-flow system. Due to the constraint of cost and scale, the focus of the IMX test was placed on the low-speed inlet flowpath that feeds the turbine engine. An earlier test effort[16] had focused on the high-speed inlet that feeds the scramjet. The results from this study indicated that the effect of the low-speed cowl would not impose difficult operability problems on the high-speed inlet. The IMX effort was conceived to address the issues associated with the low-speed inlet.

As a screening test, the IMX test had limited data recorded to indicate low-speed inlet performance, unstart stability and distortion. Performance maps were screened both at design and off-design Mach numbers. Mode transition scenarios were simulated by connecting a path through the steady-state maps. Only supercritical operability of the high-speed inlet was assessed. The results of the IMX screening test, together with the earlier test of the high-speed inlet, have bolstered confidence in the design approach. Further, the IMX test results have enabled the identification of mode transition procedures that will be investigated in the large-scale integrated propulsion system test.

INLET DESIGN APPROACH

VEHICLE / ENGINE INTEGRATION

The IMX inlet design effort began with a set of constraints to develop a representative propulsion flowpath. The key feature of the design was the split-flow requirement. The high-speed inlet was designed for a dual mode ram/scramjet (DMR/SJ) at Mach 7 cruise, and the low-speed inlet was sized for a Mach 4 turbine engine. The turbine engine becomes cocooned beyond its Mach 4 peak operating point. Conceptually, this propulsion system was selected to meet the needs of the first stage of a two-stage-to-orbit vehicle. The low-speed inlet design was integrated into the aerodynamic lines of the Mach 7 high-speed inlet. A forebody compression vehicle with nominally two-dimensional flow would feed the dual inlet ducts. A sketch that illustrates a hypersonic aircraft with a dual-flow, over/under, propulsion system (configured for start of transition at Mach 4) is presented in figure 1. Details of the aerodynamic design of the dual-flow hypersonic inlet for mode transitioning research are given in reference 17. Traditional design techniques were used in an innovative approach to balance the aerodynamic and mechanical constraints to create a new TBCC inlet concept. The report[17] provides a complete description of the design approach, integration of the low-speed inlet into the high-speed inlet, estimated inlet performance, inlet contours, and proposed variable geometry.

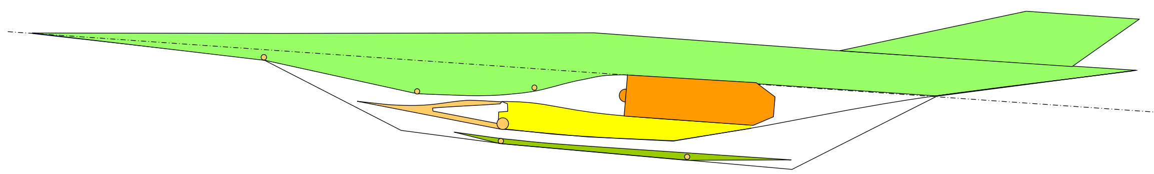


Figure 1: Dual flow / split inlet integrated onto a hypersonic vehicle. Centerline cross-section.

LOW-SPEED INLET DESIGN

Hypersonic TBCC propulsion system features present some unusual design challenges for low-speed inlet. A bulleted list of the most critical of these design challenges is given in figure 2.

Low-speed inlet Design Challenges

- The high-speed aerodynamic lines become a constraint on the design of the low-speed inlet.
- Two propulsion systems operating over different Mach number ranges with very different airflow requirements dominate the inlet system design.
- The low-speed inlet must include variable geometry as a means of matching airflow variations of the turbine engine (variable cowl and probable variable ramp).
- Acceptable inlet performance and operability must be provided.
- One characteristic that represents an extreme challenge to the low-speed design is ingestion of the forebody boundary layer.

Figure 2: Elements of low-speed (or turbine engine) inlet design, an approach to high performance.

The high-speed flowpath is longer than the low-speed flowpath due to the lower compression shock angles. As a consequence, the low-speed inlet design can be integrated into the existing high-speed inlet aerodynamic contours. The aerodynamic lines of the high-speed inlet impose significant constraints on the design of the low-speed inlet. When integration of the low-speed inlet into the compression field of the high-speed inlet is considered, the amount of compression external to the cowl lip is limited to a less than desirable amount for the low-speed inlet.

Within this constraint, the low-speed IMX inlet was designed to provide high performance from takeoff to Mach 4 flight conditions. At Mach 4, the low-speed inlet must be able to allow operation of the high-speed propulsion system which operates through Mach 4 to Mach 7. Integration of a low-speed inlet into the flow field of a high-speed inlet with multiple flow streams, large boundary layers, extensive variable geometry, and engine mode transitioning presented multiple challenges. The design includes consideration of all of the normal subsystems required by traditional supersonic mixed-compression inlets. These systems include a subsonic diffuser, multiple bleed regions, overboard-bypass, controls, stability system(s), and vortex generators. Both low-speed and high-speed inlets have variable geometry (rotating) cowl lip sections, and the low-speed inlet has a variable geometry ramp. Proposed inlet variable geometry schedules during mode transition and for off-design operation are also included in the reference design report[17]. The IMX inlet design is an aerodynamic concept that offers high performance and operability and is compatible with a realistic and practical variable geometry system.

For the low-speed inlet, flow rates reported in this paper are referenced to the freestream capture of the low-speed cowl. This reference capture is based on the low-speed inlet cowl height, H_{ls} = $0.57192 * H_{hs}$. When engine and bleed flow rates are quoted, they are normalized by this capture height. Specifically, the bleed flow rates, $m_b/m_o = m_b/m_o|_{hs} * 0.57192$ and engine flow rate is $m_2/m_o = m_2/m_o|_{hs} * 0.57192$.

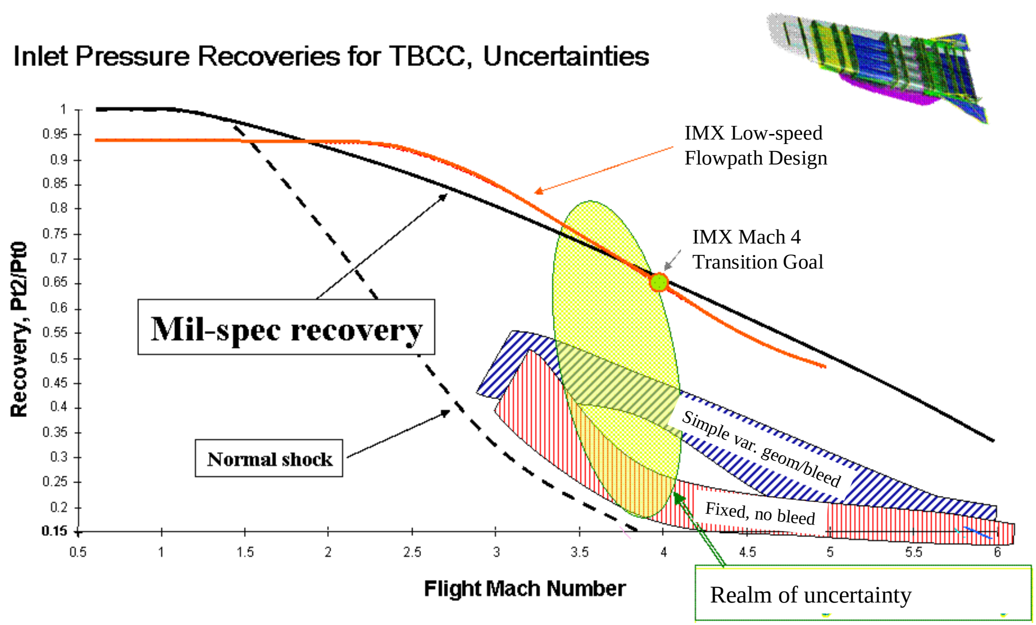


Figure 3: Range of typical inlet recoveries. Hypersonic inlet performance is highly dependent on design. Recovery can vary by a factor of 4 times.

The design for the low-speed inlet was developed to achieve high performance, which is typified by Mil-Spec E-5008B inlet total pressure recovery. Figure 3 shows the targeted IMX low-speed flowpath inlet recovery. Past experience with mixed-compression inlet designs has indicated that achieving mil-spec recovery requires highly complex inlet designs incorporating variable geometry and compartmented bleed regions. For reference purposes, recovery ranges typical of various levels of inlet design complexity are spotted on the curve. Simple variable geometry with bleed is typified by ramp/throat duct area control with throat bleed. Fixed geometry with no bleed further simplifies the design with significant increases in inlet losses resulting from the high throat Mach numbers and high loss shock-isolator feature. Evident from this curve is the high dependence of the low-speed inlet recovery on the design approach. The range of recoveries from 0.15 to over 0.6, (a magnitude of 4 times), is noted as a 'realm of uncertainty' in figure 3 for vehicle system studies. Until inlet design complexity is defined, inlet performance is uncertain. An inlet with a recovery at the lower end of the realm of uncertainty would nominally require four times the turbine frontal area to achieve the same level of thrust or acceleration as one operating at the upper bound[13]. Consequently, the turbine engines would be twice the size (length-scaled) and there would be an increase in vehicle dry weight and loss of fuel volume for typical aircraft/missions. For this effort, a high-recovery, low-speed inlet design with significant complexity was selected to understand the upper bounds of TBCC low-speed inlet performance.

DESIGN FOR INLET MODE TRANSITION

The key element of the inlet aerodynamic design is to provide high quality flow to both the turbine and scramjet engines. Figure 4 shows an axial cross-section with most of the major aerodynamic features of the IMX. In a typical installation, vehicle forebody compression is used to add to the overall inlet compression. The turbine flowpath is shown above the scramjet for this over/under propulsion system in this figure.

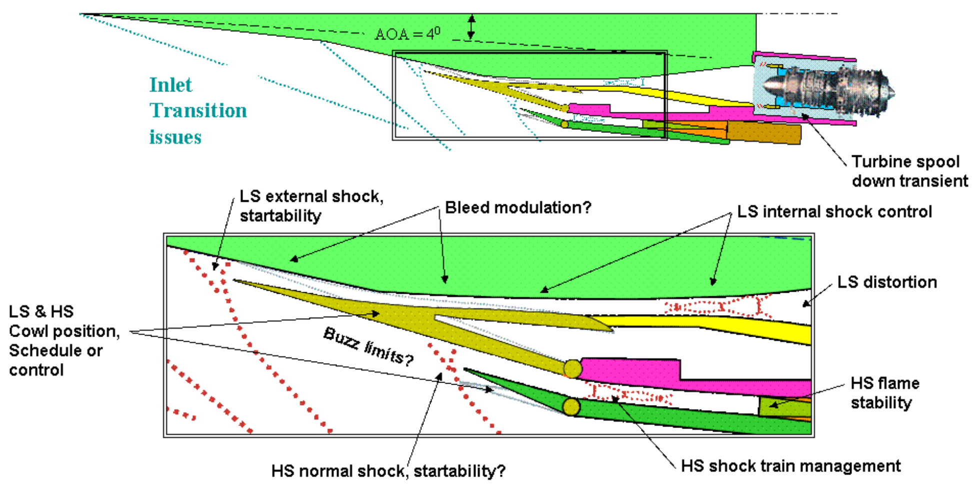


Figure 4: Mode transition sequences: Mach 4 shock phenomena that can occur during transition from dual inlet operation to the single high-speed inlet operation.

The inlet was designed for mode transition at Mach 4. The detailed inset shows the variable cowl geometries as the splitter or low-speed cowl is closed, reducing flow to the turbine engine and increasing flow to the scramjet. Shock wave structures are also shown. Beyond a traditional design approach to the mixed-compression low-speed inlet, an additional constraint had to be considered for TBCC mode transition. This constraint is the ability to close the inlet so that the ramp and cowl surfaces did not interfere mechanically through the entire range of motion. In a mixed-compression inlet a terminal normal shock is positioned at or just downstream of the throat to deliver subsonic flow to either the turbine or the dual-mode ramjet. For the ram/scram flowpath, the terminal shock becomes a 'shock train' that is composed of wall separations, lambda oblique shock waves and centerline normal shocks.

In the low-speed inlet, the length of internal compression (from cowl lip to throat) is significantly longer than in traditional supersonic inlet designs. This additional length is due to two reasons: the integration of the low-speed inlet into the high-speed inlet design and, secondly, the use of a forebody compression vehicle. The added internal length coupled with the ingested forebody boundary layer would typically contribute to lower than optimal recovery. To compensate, additional bleed flow capability was integrated into the inlet model. The added bleed could then be varied to understand the relationship between bleed and recovery.

During mode transition, uncertainty exists as to how the shock wave and flow field can be managed to provide steady flow to the two engines, turbine and DMS/RJ. Mixed-compression inlets can experience 'unstart', which is a dynamic flow condition in which the internal shock waves are violently expelled from the inlet. Following an unstart event, the shock pattern can enter a periodic oscillation known as inlet 'buzz'. This unsteadiness further complicates mechanical design with uncertain dynamic loading and cyclic fatigue concerns. Both unstart and buzz most likely will cause the turbine to stall and also may cause flame-out of either engine. Therefore, inlet unstart and/or buzz, similar to turbine engine stall, are conditions to be avoided. However, peak engine performance (due to high inlet recovery) also occurs right before inlet unstart. The balance between the two objectives, stability from unstart and high total pressure recovery, is a major objective of any supersonic inlet design.

Figure 5 illustrates the inlet geometry configurations at multiple flight conditions. Initially shown is the high-speed inlet design contour at Mach 7. From this contour, the low-speed inlet was developed using both variable cowl and ramp features. This sequence shows how the geometry of the inlet varies as the flight Mach numbers increase from take-off (M=0) through mode transition (M=3-4).

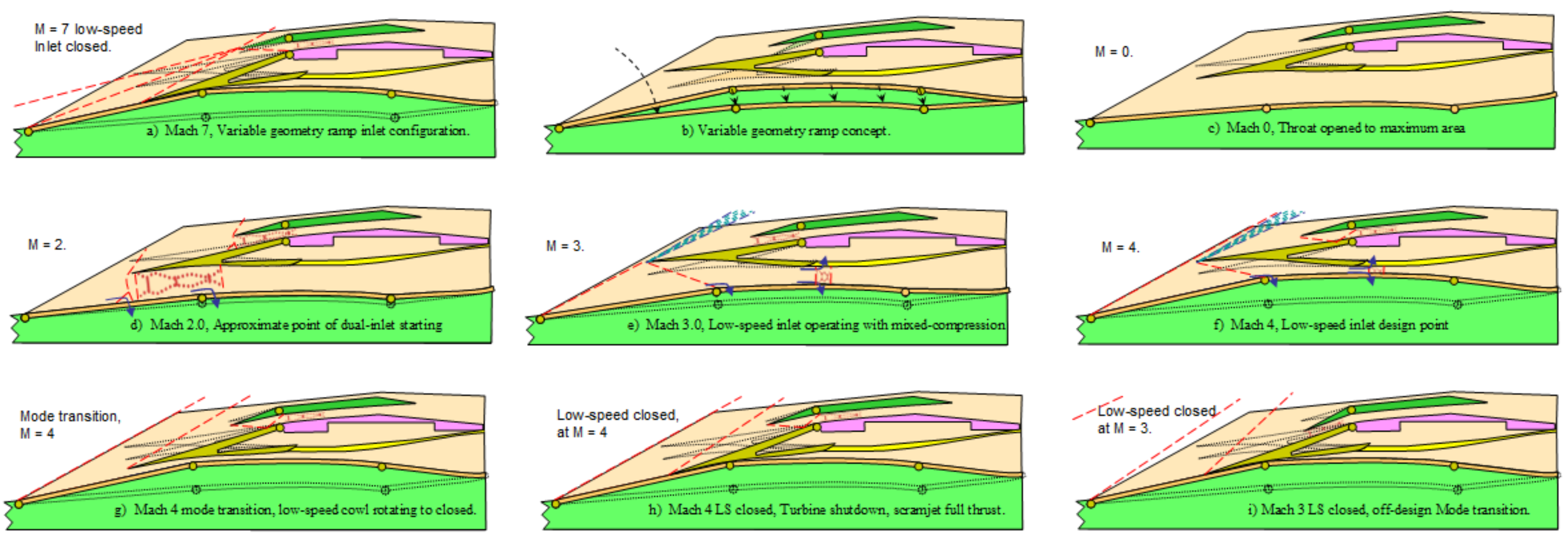


Figure 5: Mode transition concepts: Design point configuration, variable geometry as a function of Mach number including transition sequences.

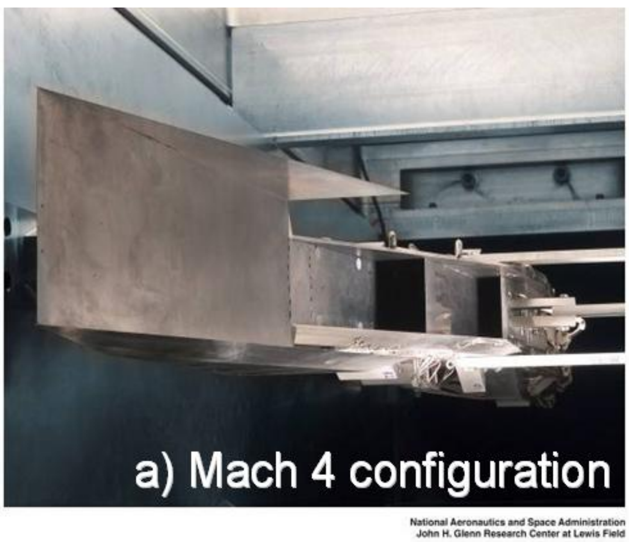
At low Mach numbers (up to Mach 2) the ramp is collapsed to provide the largest throat area and pass the most flow. An open throat is particularly critical at transonic flight conditions, where thrust pinching can occur. At Mach 2 to 3, the inlet is started, which means that an internal shock pattern is established. As this happens, more bleed regions become active and the throat area can be reduced to improve inlet recovery. From Mach 3 to 4, the cowl remains near a fixed design point while the ramp geometry continues to change. The variable ramp thereby provides the proper throat area reduction for increased Mach number. At mode transition, the low-speed cowl begins to close. The high-speed cowl is also varied to provide maximum flow with proper ramjet/scramjet stability.

Various engine scenarios are possible, but the anticipated baseline concept is one in which the DMR/SJ is ignited at Mach 4 with the turbine at full thrust. Mach 4 transition was chosen to be compatible with research activities that are focused on high Mach turbine engine technologies (RTA/HiSTED[6,8]). As the turbine flow is reduced by one half, constant corrected flow is maintained. After this point, the engine will spool down as a function of rotational inertia as the turbine fuel is chopped. The ramjet/scramjet should be providing sufficient thrust for positive vehicle acceleration at this point. Due to uncertainties about the proper transition Mach number, the inlet design accommodates the investigation of a range of transition speeds from Mach 3 to 4. However, since this low-speed inlet is designed for Mach 4, low-speed inlet performance is increasingly compromised as the transition Mach number is reduced. However, inlet performance at Mach 3 is still sufficient to perform valid mode transition research.

SMALL-SCALE SCREENING EXPERIMENT

MODEL HARDWARE

The first phase of the experimental approach was to implement the IMX aerodynamic design into a small-scale model for testing in the 1'x1' SWT[18]. The small-scale concept-screening model incorporated the variable cowl geometry features. For simplicity, a remotely variable ramp feature was not included. However, parametric hardware provided the capability of testing the inlet with alternative ramp geometries. Photographs of the model installed in the 1'x1' SWT are shown in figure 6. In the Mach 4 configuration, the two inlet apertures can be seen as dark rectangles, figure 6(a). In the photograph for the Mach 7 geometry, figure 6(b), the low-speed inlet is closed. The vehicle forebody ramp is simplified by using a straight wedge with triangular flow fences to ensure two-dimensional flow while minimizing tunnel blockage.



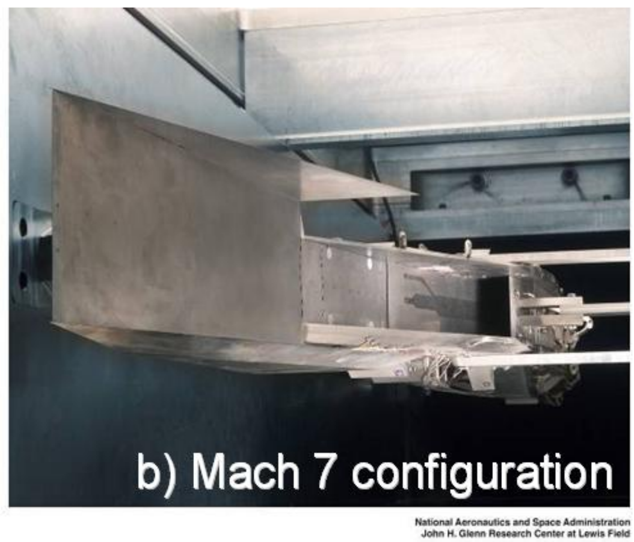


Figure 6: Photographs showing IMX model installed in the 1' x 1' supersonic wind tunnel. Low-speed cowl position: a) Mach 4 configuration for mode transition and b) Mach 7 configuration, high-speed inlet design.

Figures 7 and 8 show the 1'x1' SWT small-scale IMX model as a schematic and photographs taken during shop assembly. The mechanical part breaks can be seen in the schematic in figure 7. Also shown are various compartments for bleed needed to manage the shock wave / boundary layer interactions. The variable cowl features are also evident in the figures. More subtly, the ramp geometry variation can be seen. As mentioned, the small-scale IMX model did not incorporate a remotely variable ramp design. Instead, the model could be assembled in any one of three configurations. In the schematic of figure 7, the Mach 4 geometry is shown with a red cross-hatched second ramp surface. A Mach 3 ramp was also tested, and is suggested by the light blue cross-hatched second ramp surface (configuration VGR, Variable Geometry Ramp). The mechanical design for these two configurations allowed for reuse of many of the downstream ramp parts. The cyan colored part shows the Mach 4 subsonic diffuser ramp geometry, while the Mach 3 geometry is not shown. A third geometry was also tested as a second alternative for Mach 3 operation. This geometry is not shown but is composed of the Mach 4 ramp surfaces coupled with a reduced thickness splitter/low-speed cowl geometry. This alternate Variable Geometry Cowl, VGC, increases the throat area with a collapsing cowl feature that may eliminate the need for a variable geometry ramp.

The model was of a bolted construction that used o-ring seals on the moving cowl parts and silicone-based red RTV sealant on static surfaces. The characteristic height of the inlet at this scale was H_{hs} = 4.943 inches (inviscid design) and the overall length was about 4 feet long. The characteristic height is used in the reference area for flow capture calculations. The actual cowl lip height for the small-scale IMX model was adjusted to 5.0008 inches to compensate for boundary layer growth. These heights are measured vertically from the ramp leading edge to the high-speed cowl lip when configured for Mach 7 operation. Cowl lip adjustments are detailed in reference 17. The width of the small-scale IMX model was set to match the simulated engine diameter, 1.821 inches at this scale.

Attached to the back end of the low-speed inlet was a short length of cylindrical pipe followed by a 16.5 degree conical plug. The plug translated axially into the pipe to both control and measure the mass-flow. The plug annular area was correlated to corrected mass-flow that mimics steady-state turbine engine performance.

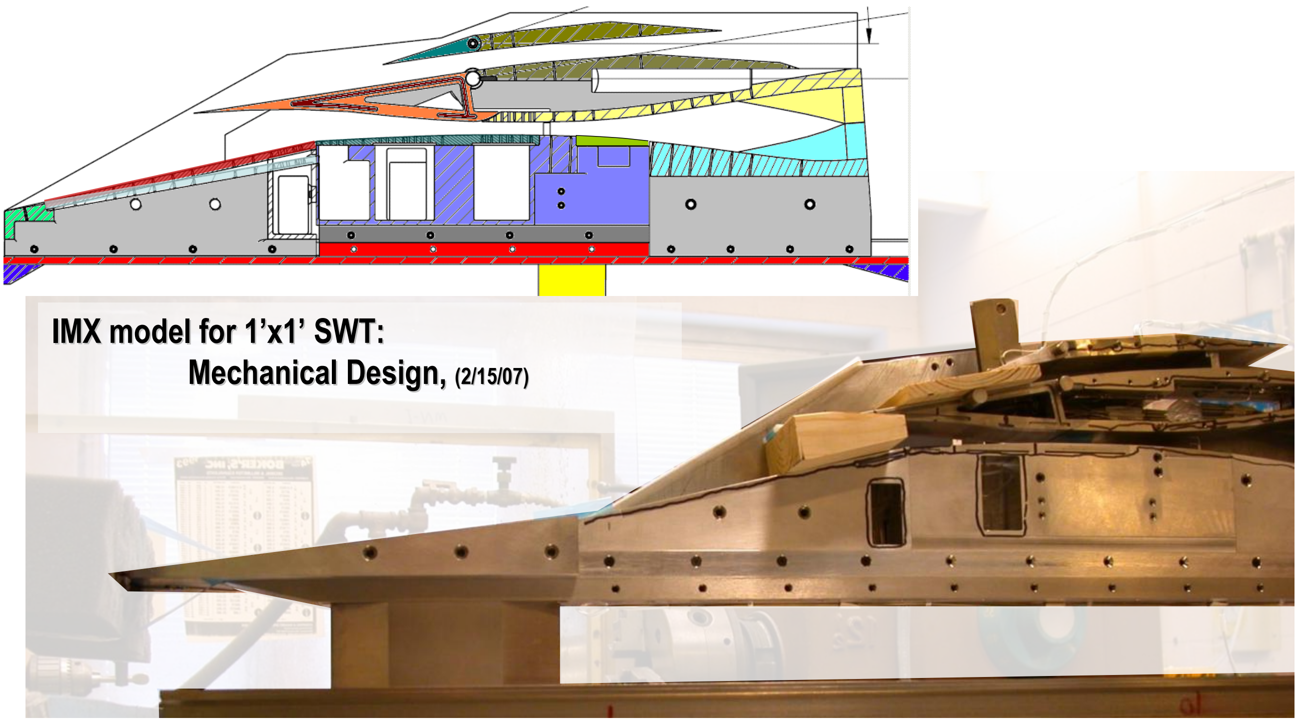


Figure 7: IMX model mechanical design and shop assembly.

The photograph in figure 7 shows the physical geometry of the IMX inlet with the sidewall removed. (Note that wooden block wedges are inserted into the two inlets to prop the rotating cowl lips open). Instrumentation included 144 steady-state and 5 dynamic pressures. A set of 4 rakes were located at the end of the low-speed inlet to measure total pressure recovery and and also to indicate distortion. These rakes had a total of nine tubes arrayed in two rings and a center-point tube, equally area-weighted. Thirty-six (36) static pressures along the low-speed inlet ramp surface gave a primary indication of the normal shock location. The two rotating cowls and the low-speed flowpath metering plug positions were measured with LVDTs (linear variable displacement transducers). The steady-state measurements were recorded and reduced into engineering units using ESP modules for the pressures and a Neff® system for analog position measurements. The steady-state measurements were further processed using GRC's internal Escort data reduction system. The Escort system provides real-time display and plotting of measurements and calculations to allow intelligent data collection.

The time varying signals, (dynamic pressures and positions), were recorded by a separate PC-based system. The sampling rate was generally 100K samples per second for 3 seconds. The machine displayed real-time signals to mimic oscilloscope output. These traces were monitored in addition to video output of schlieren optical visualization of the external shock wave pattern. The real-time dynamic displays coupled with characteristic changes in the steady-state pressure distributions were used to detect unstart and buzz inlet conditions.

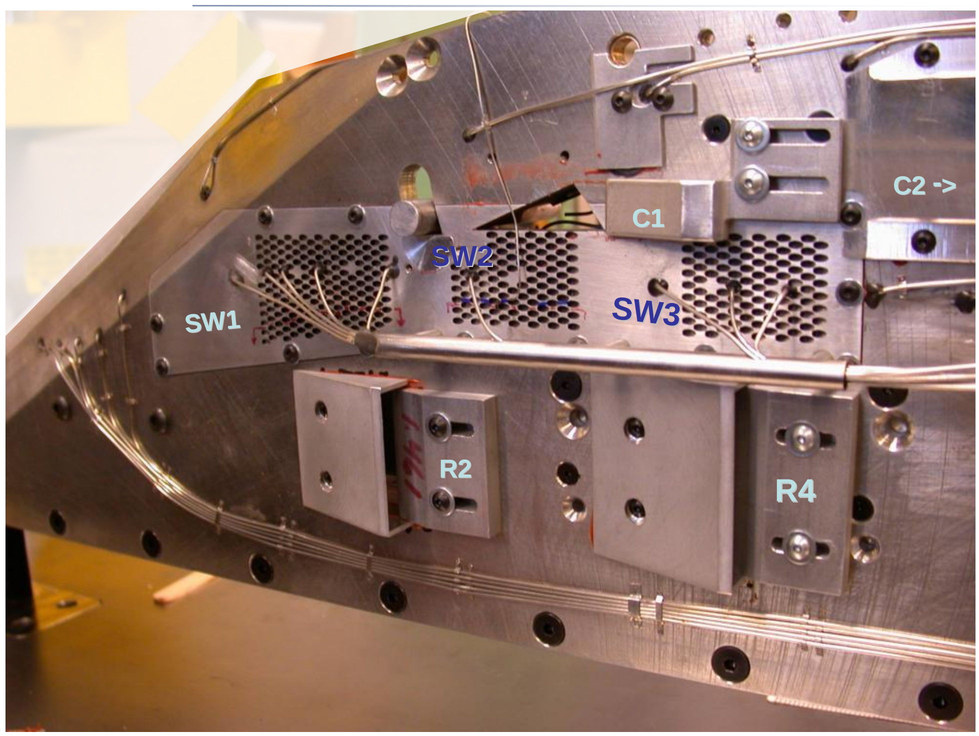


Figure 8: IMX model photograph showing sidewall and bleed exits. Low-speed inlet design is dominated by nine bleed regions.

Figure 8 shows a photograph of the external surface of a sidewall. Most evident are the compartmented bleed exits: two for the cowl bleeds, C1 & C2, three on the sidewall, SW1, SW2 & SW3, and four on the ramp surfaces, R1 to R4. (R1 & R3 are not visible because they exit on opposite sidewall). Also the cantilevered cowl was difficult to actuate in a model of this small scale. Note the actuator rod for the low-speed cowl, (just above the SW2 label), which passes through openings through the sidewalls. The resulting sidewall openings provided structurally sound cowl actuation but somewhat compromised the aerodynamic surfaces. The openings introduced both a leakage path and a local disturbance to the airflow.

CFD SUPPORT ANALYSES

Concurrent to the mechanical design of the 1'x1' small-scale IMX model, CFD analyses were conducted to validate the inlet design. Discussed herein are CFD predictions and some results obtained concurrent to the active testing period. Post-diction CFD will continue and will be reported in subsequent documents.

In support of the test objectives, the CFD effort was primarily focused on the low-speed inlet performance and operability. From the original flow contours[17], grids were generated as input to a Reynolds-averaged Navier-Stokes (RANS) solver, the Wind-US code[19-21]. Wind-US is developed and managed by the NPARC Alliance. The NPARC Alliance is a partnership between NASA Glenn Research Center, USAF Arnold Engineering Development Center, and The Boeing Company. The Wind code has matured as a multi-zone, structured grid compressible flow solver, offering a variety of turbulence models. These turbulence models include several zero-equation models, Spalart-Allmaras and other one-equation models, and the Chien k-ε and Menter SST two-equation models. Most of the analyses shown in this paper used the Menter SST model. Initially, the inlet was analyzed with supersonic flow-through conditions that simulate supercritical inlet operation without any downstream back-pressure. These predictions were used to verify the inlet design intent: the shock wave structure, boundary layer development and throat Mach number.

The next level of computational complexity involved back-pressuring the CFD solutions, which is analogous to reducing the corrected flow with the conical plug or matching the turbine engine flow. The back-pressure effect determines the inlet recovery performance and stability. Experimental and numerical results from back-pressuring of the inlet are typically plotted on an inlet characteristic graph of recovery versus engine flow ratio. Often termed a ‘cane curve’ due to its shape, the knee or bend in the ‘cane’ is typically the best inlet operating point. The top of the cane is an indication of inlet operability or stability.

The most recent CFD efforts involved providing guidance for inlet testing. A major testing parameter was the location and amount of bleed in each of the nine compartments. As mentioned previously, preliminary CFD results validated the design intent. However, the comparison between experiment and CFD analysis did not indicate full agreement and suggested that changes were needed to be made to both the testing matrix and the CFD modeling approach. Experimental results showed that the low-speed inlet throat Mach number (~Mach 1.5) was somewhat greater than both the design intent and CFD predictions. This result has led to another test entry in the 1’x1’ SWT. CFD analyses are continuing to help resolve and/or understand this discrepancy. Finally, both experiment and CFD suggest a significant forward corner interaction due to imperfect two-dimensional cancellation of the cowl shock wave on the ramp shoulder. This result led to experimental testing of a cutback cowl configuration. Each of these results will be discussed in more detail in following sections.

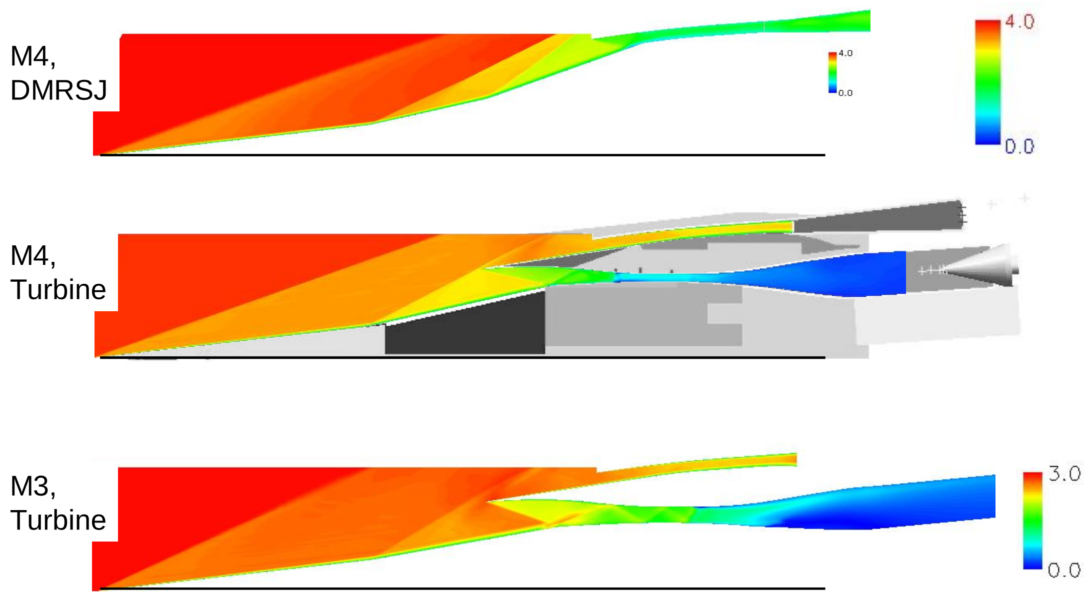


Figure 9: Computational Fluid Dynamics verified mode transition concept. Early CFD showed expected flowfields through mode transition.

An early RANS solution showing Mach number contours is shown in figure 9. These calculations were also used to check the IMX CAD model with the original MOC design intent. For the inlet geometries configured for mode transition at Mach numbers of 4 and 3, solutions were obtained both prior to and following closure of the low-speed cowl. Overlaid in the center solution of Mach number contours is the mechanical geometry of the inlet model. Note especially the depiction of the conical plug on the low-speed flow path. The top solution shows the DMR/SJ configuration, in which the low-speed splitter cowl is closed and all the flow is ducted into the high-speed flow path. The high-speed inlet / isolator Mach number is about 2. The center solution shows the Mach 4 solution with the low-speed cowl open to its design position. The low-speed inlet cowl shock is generally cancelled by the shoulder and

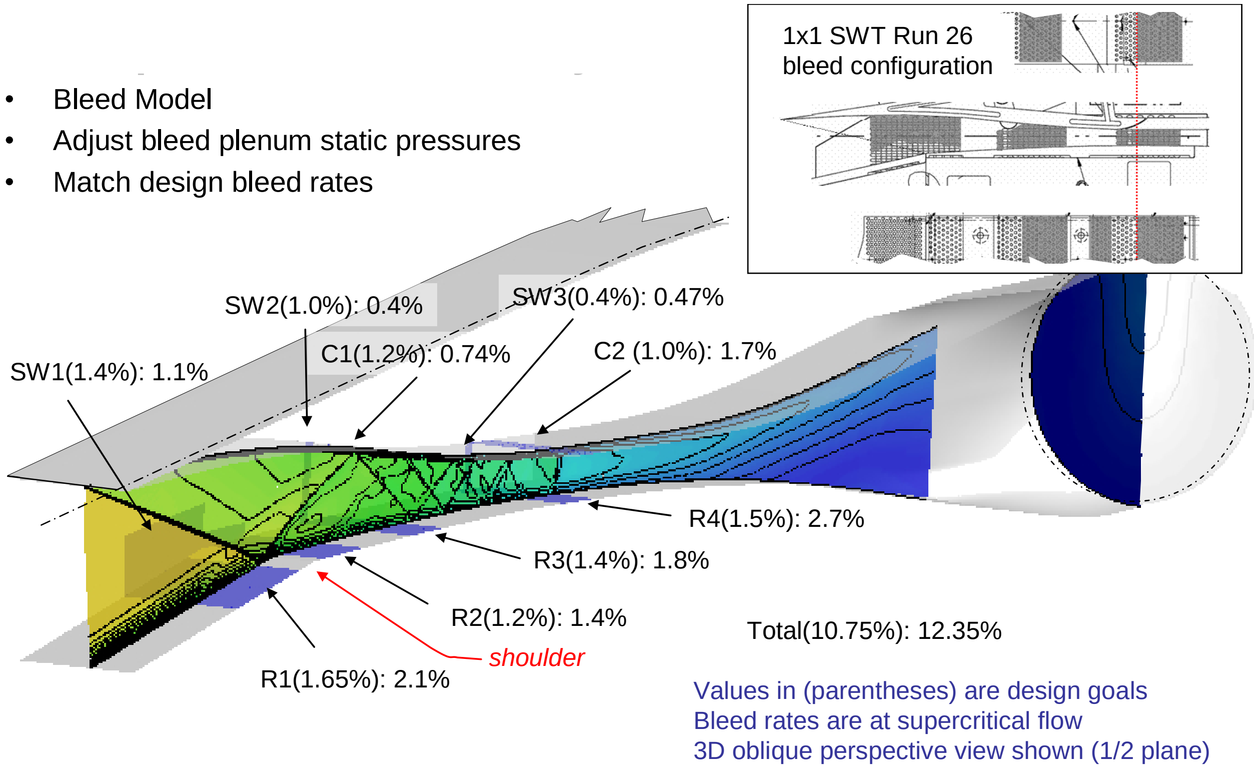


Figure 10: Low-Speed Inlet Bleed CFD Study is able to model complexity of inlet bleed design. The complexity is needed to predict performance.

flow is just above Mach 1 in the throat. In this solution, bleed has been modeled in the low-speed inlet; bleed was needed for the CFD prediction to establish started inlet operation. The solution at the bottom shows the Mach 3 dual flow path operations. This condition represents off-design mode transition. Note the imperfect shock cancellation at the shoulder for the low-speed inlet. For both mode transition cases, the high-speed flowpaths lack high compression and have high throat Mach numbers. The resulting low static pressures may suggest ignition challenges for scramjet combustion.

As indicated, inlet performance prediction remains a significantly challenging and complex undertaking. Figure 10 shows details of a back-pressured CFD analysis. Each of the compartmented bleeds was modeled to match design intent bleed flow rates. Also shown in the figure, values in parentheses are design goals. Bleed rates are levels modeled with supercritical flow. A 3D oblique perspective view is shown (1/2 plane).

A constant plenum pressure bleed model was used, mimicking a fairly complicated variable bleed exit like a poppet valve or other ‘smart’ valve. Stability bleed and valve exit control have been shown to provide greatly enhanced terminal shock stability in mixed-compression inlets[20,21]. Constant pressure bleed control was used to provide a large stability margin in the Mach 5 inlet[3]. The CFD bleed pattern of this analysis was similar to a configuration that was investigated during the 1’x1’ SWT test, (run 26). Note that the complexity of the compartmented bleed patterns is important to correctly analyze a mixed-compression inlet flowfield. Misplaced bleeds and inadequate bleed rates will result in ‘computational’ unstarts. In general, with careful bleed specification and back-pressuring methods, CFD was able to model the complexity of inlet bleed. Modeling efforts[24] continue to refine the bleed boundary conditions implemented in CFD tools. This CFD solution indicates that the bleed design (location, amount, compartmentation) was sufficiently valid for started inlet operation.

With the baseline computation established, a detailed examination was made of the shock/boundary layer interactions. In figure 11, the cowl shock / shoulder interaction is shown as a 3D oblique view looking into the ramp/sidewall corner. Imperfect cancellation is evident with pressure feeding forward in the corner.

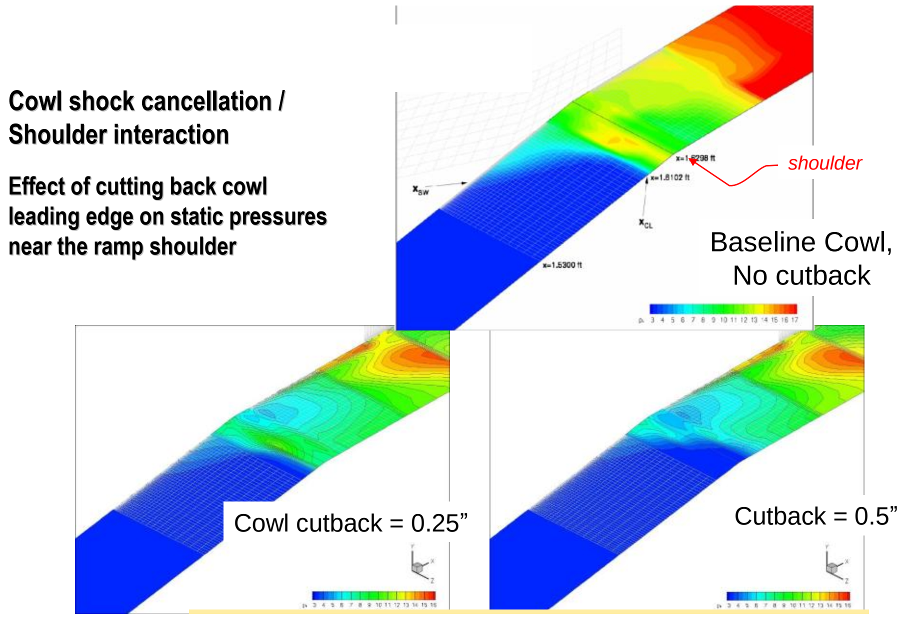


Figure 11: Low-Speed Inlet CFD Study investigated adverse shock interactions at the shoulder of the low-speed duct.

To reduce the interaction, the CFD study explored cutback cowl variations. The cowl leading edge was moved downstream along the initially flat internal surface by 0.25” and 0.5”. Both configurations reduced the forward corner interaction, but led to flow expansion near the shoulder on the inlet centerline. The loss of centerline compression could reduce inlet performance. The cutback also reduces capture and, consequently, reduces the thrust and recovery. The effect of the cutback on quantified total pressure recovery has not been predicted since full back-pressured analyses have not yet been done. However, the super-critical results were encouraging enough to warrant experimental testing of a cutback cowl configuration, for which a more conservative 0.1 inch cutback was chosen.

CFD was used to investigate inlet mode transition at Mach 4. Mode transition is one of the greater challenges for applied CFD analysis. Figure 12 illustrates a series of CFD analyses that were conducted to examine the flowfield as the low-speed cowl was rotated toward the closed position.

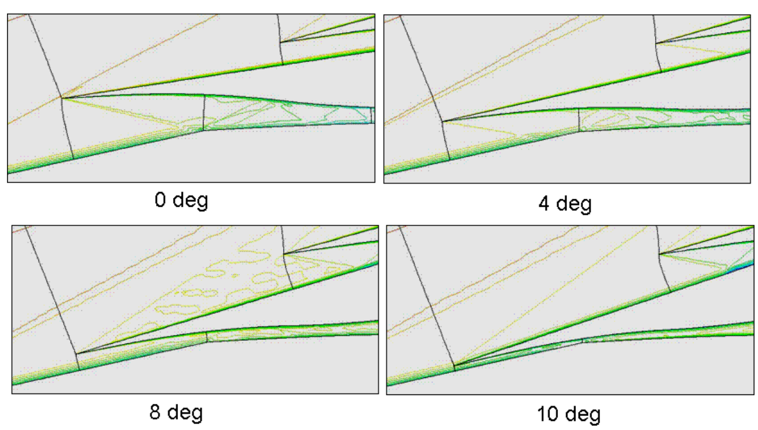


Figure 12: Mode Transition at Mach 4 with Low-speed inlet’s cowl rotating to closed position. Sequence of 2D steady-state solutions at low-speed cowl angles suggests that inlet mode transition is possible.

This series at various settings of low-speed cowl angle was analyzed with 2D steady-state solutions. Lower fidelity, 2D analysis was used to reduce computational cost. This quick study provided a preliminary verification that smooth inlet mode transition was achievable with this inlet concept. Eventually, this computational study will be expanded using fully three-dimensional grids and solutions.

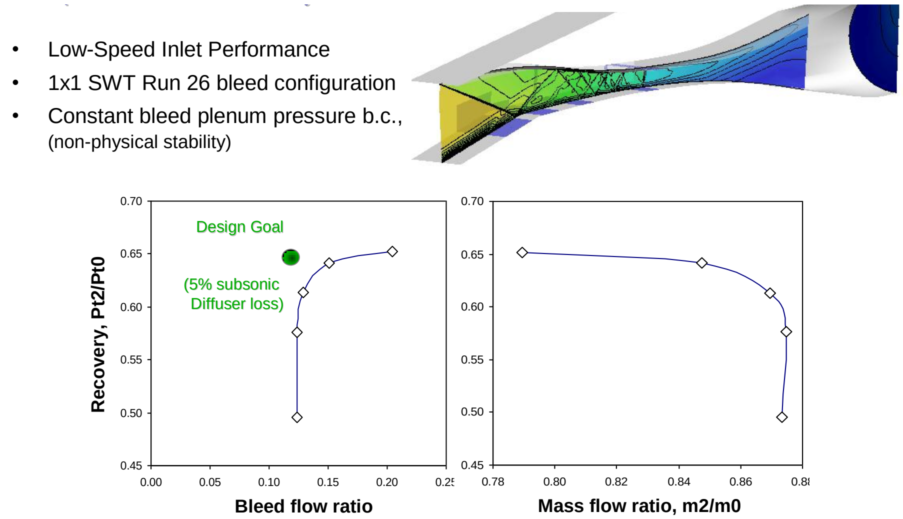


Figure 13: Back-pressured CFD Study: Performance ‘Cane’ Curves. Inlet performance versus flow ratio, CFD analyses suggest LS inlet performance is obtainable.

With adequate bleed models, manageable boundary layer interactions and some indication that mode transition would be possible for the inlet concept, the focus of the CFD analysis was shifted to predicting inlet performance. Back-pressure was simulated by varying the low-speed inlet exit area. As shown in figure 13, five cases were converged to steady-state. The bleed was set up to closely match a tested configuration (run 26 of figure 10) with the constant plenum pressure bleed boundary condition. This approach mimics stability bleed exit valve control[20]. Simple fixed exits were used in the small-scale model test; therefore the CFD should predict greater stability than could be demonstrated by the small-scale research model. However, the knee of the performance ‘cane’ curve should be fairly well predicted. In the figure, the CFD results show performance only about 2% (0.02) lower than the goal recovery. This is a very encouraging result when the original uncertainties of the design are considered. Particularly, the thick forebody boundary layer and extended internal length of the supersonic diffuser would be expected to cause difficulties in achieving the design goal. Subsequent CFD analyses have also predicted performance levels to be very near the design goals that were reported in the design report[17].

A secondary objective of the small-scale test was to make a rough assessment of the total pressure distortion field of the low-speed inlet. To complement this objective, distortion levels were calculated from the CFD solutions. This early CFD prediction did not model the refined bleed patterns of Run 26, (figures 10 & 13). For the simplified bleed configuration modeled, nearly 30% bleed was needed to maintain started inlet operation. As of this report, none of the CFD solutions have incorporated vortex generators in the subsonic diffuser. Vortex generators are used to control separations in the subsonic diffuser and improve distortion fields for

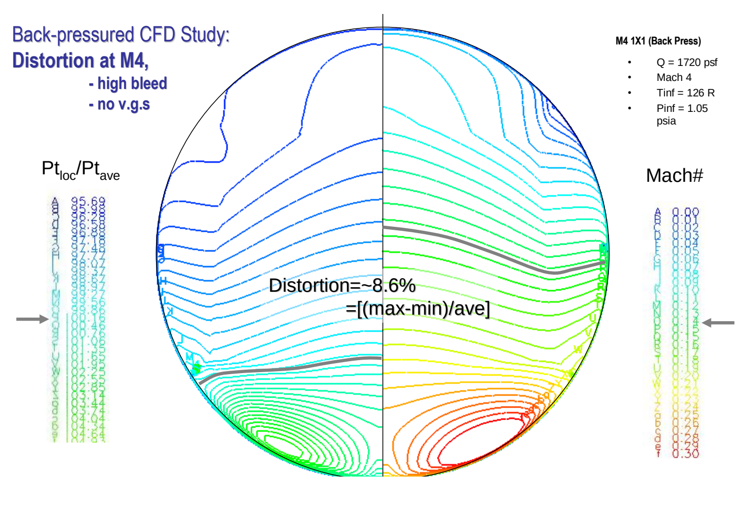


Figure 14: Back-pressured CFD Study showing AIP cross-section with distortion flowfield for Mach 4, high bleed flows and no vortex generators. CFD indicates distortion level may be high.

better turbine engine compatibility. With that caveat recognized, figure 14 shows a distortion pattern from the inlet at the turbine engine face, a cross-section known as the Aerodynamic Interface Plane (AIP). The distortion magnitude, (D2=[max-min]/average), of nearly 9% is significant for many turbine engines. Levels below 6% are generally considered benign while levels above 12% would generally cause engine stall[12]. This simple analysis provides only an initial indication of the relevant distortion quality. The characterization of distortion necessarily entails much more complexity due to engine sensitivities to many AIP factors: dynamic field, circumferential and radial patterns, engine flow/entrance Mach, and occasionally others.

SMALL-SCALE SCREENING RESULTS

The first phase of IMX testing included a series of 55 run days. Most testing was conducted at the Mach 4 mode transition design point. Results from the Mach 4 test assessed the inlet performance and stability for multiple bleed patterns and amounts. The stability for the small-scale inlet was limited due to the utilization of a fixed exit on each of the bleed plenums. A rather unique phenomenon was observed for this inlet that involves a 'popping' behavior. This unique behavior has not previously been observed in similar mixed-compression inlets, and will be discussed in more detail later in this report. Some low-fidelity measurements of AIP distortion were made with the small-scale model's limited instrumentation. The small-scale model did not include an optimized vortex generator configuration and was calculated from a limited array of engine face instrumentation consisting of nine total pressure tubes. The mode transition process was recorded as a series of steady-state maps.

Mode transition was also screened at Mach 3 for the two alternate configurations, (VGR and VGC). Additionally, limited data were recorded for these off-design mode transition geometries at off-design Mach numbers of Mach 2.5 and Mach 3.5. Performance and distortion were documented. The VGC configuration gave surprisingly good results that merit further study.

MACH 4.0 DESIGN PERFORMANCE

For the Mach 4.0 design, the major test configuration parameter that was changed was the inlet bleed pattern, one of which is shown in figure 15. Results from the Mach 4 test assessed the inlet performance and stability for multiple bleed patterns and amounts. Nearly 30 different bleed configurations were investigated to improve performance, namely to provide better recovery at minimal bleed flow.

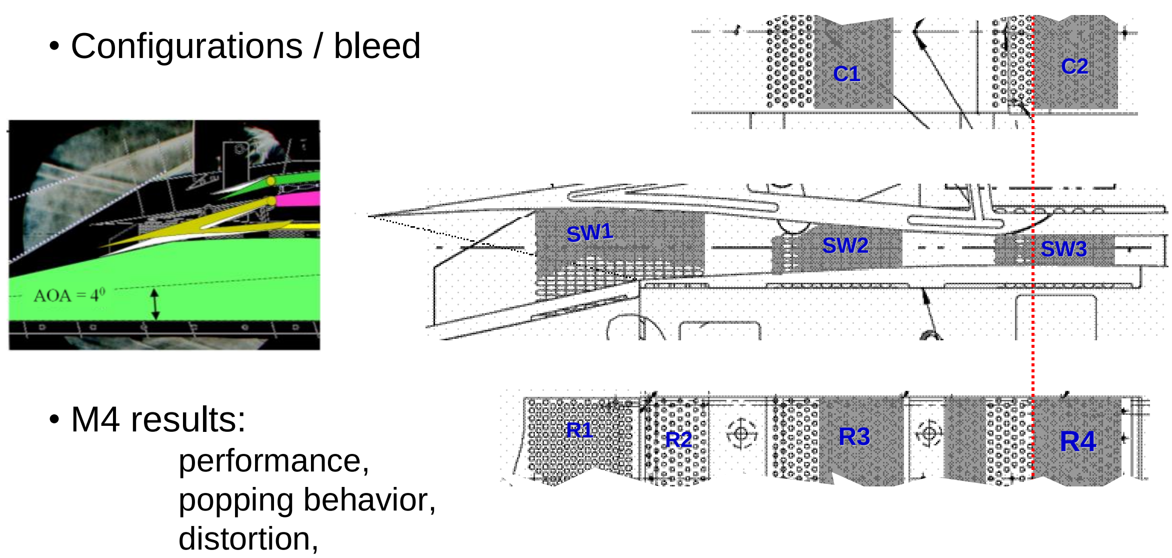


Figure 15: 1'x1' SWT screening results include bleed optimization, schlieren imaging, low-speed inlet performance at Mach 4 and off-design at lower Mach numbers.

Throughout the testing, real-time monitoring of the shock wave pattern was visible through video of the schlieren. Periodically, digital stills were taken to document the schlieren data. The Mach 4 schlieren is shown in figure 15 with an overlay of the inlet geometry schematic for orientation purposes.

In figure 16, these schlieren still photographs are shown for comparison between started and unstarted inlet operation. The top photo is similar to the small inset photo in figure 15. The inlets are started; much of the shock structure is obscured by the opaque steel sidewalls. The bottom photograph show the inlet unstarted for the same configuration but with more back-pressure than the started case. The normal shock is expelled forward of the low-speed cowl lip. This strong normal shock interacts with the ramp/sidewall boundary layers causing a very large separation that engulfs the low-speed inlet aperture. This unstarted condition was typically unsteady, and the bottom photo shows a time slice near maximum upstream expulsion. Unsteady unstarts are termed ‘buzz’ to reflect the violence of the unsteady pressure loading that can cause structural damage. Unstart is a condition to be avoided and is particularly severe from inlets with high internal contraction ratios. Screening unstart operability limits are one key to developing inlet controls. Schlieren images contribute to this unstart screening.

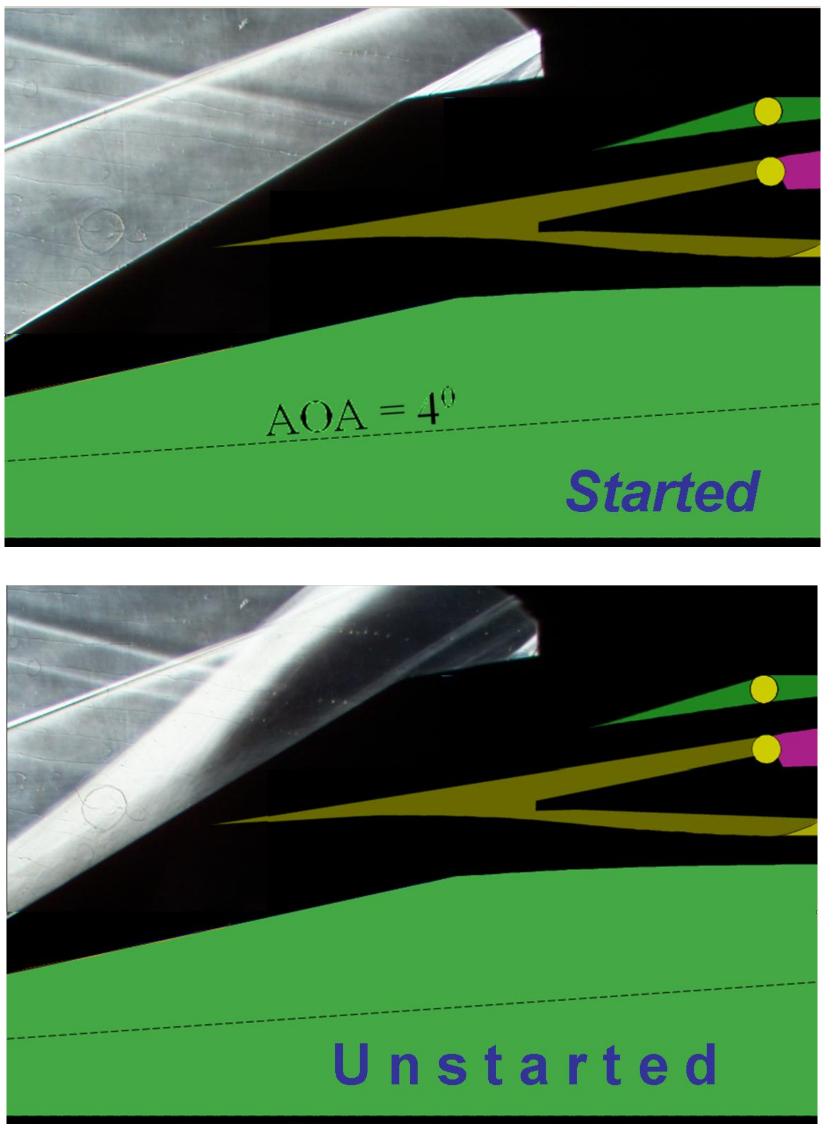


Figure 16: Schlieren photographs of IMX at Mach 4, AoA=4deg. Top photograph shows started operation. Bottom photograph shows unstart with normal shock expelled forward of the low-speed cowl lip.

Near the end of the bleed optimization test phase, the best bleed configuration was chosen to map an inlet mode transition sequence. A typical map of inlet performance, operability and mode transition sequence is presented in figure 17. A large number of cane curves are shown, and each is a data set for a specific low-speed cowl angle. At the largest cowl angle (large flow captures), the performance is within about 6% of the design recovery (0.59 vs. 0.65) Flow accounting is still being refined from the test data; it is never trivial for inlet tests and is particularly difficult for this test due to the small-scale and various leakage paths.

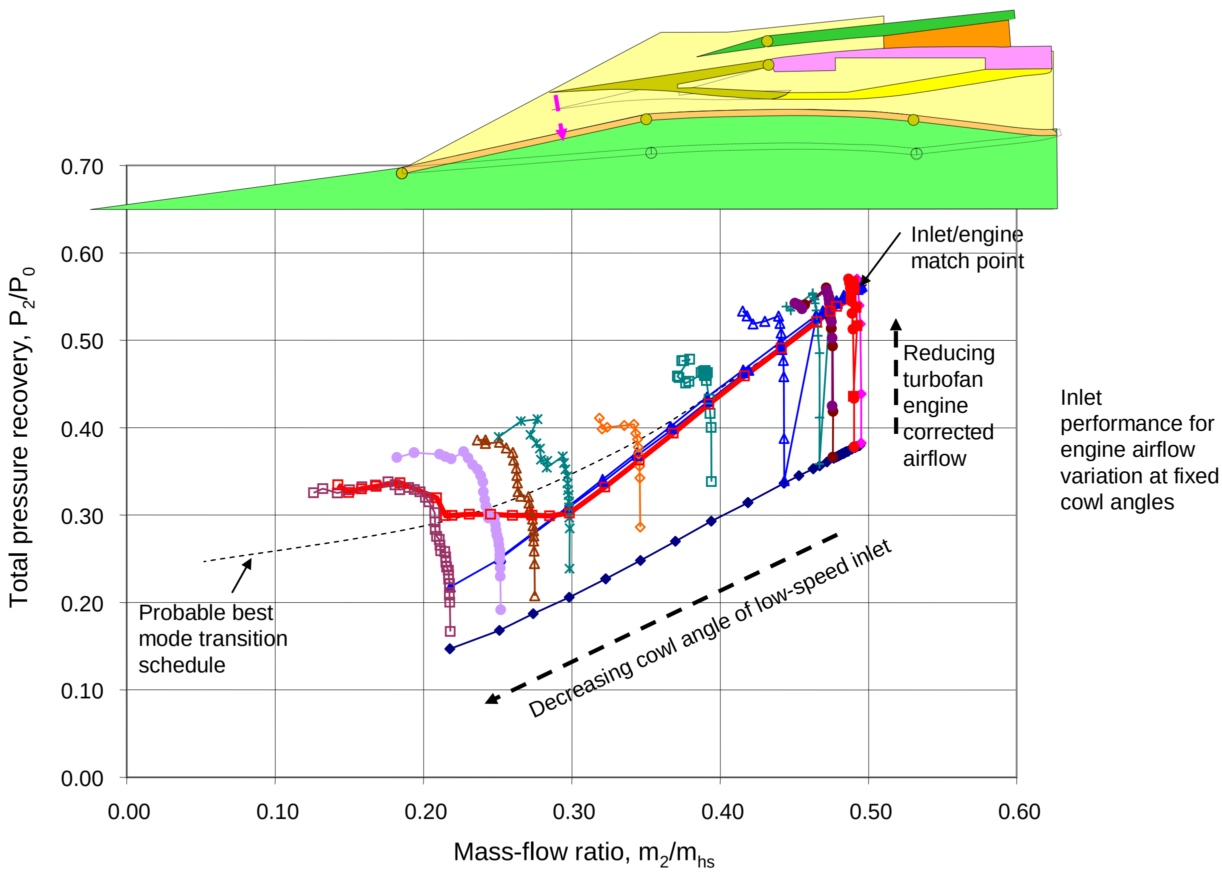


Figure 17: 1'x1' test results at Mach 4. Performance 'Cane' Curves. Inlet performance versus flow ratio, Mach 4 performance is near design goal: mode transition is smooth.

The configuration with the cowl lip at the Mach 4 design position has a large amount of internal contraction and does not exhibit the 'popping' condition, as evidenced by the cane curves at low angles of rotation. As the cowl lip is rotated toward closed, the internal contraction decreases and at some point becomes a divergent duct from the cowl lip station. In between these two extreme cowl lip positions area distributions will occur that will allow the normal shock pressure rise to shift forward in the inlet. Typically, the pressure rise would shift to the next upstream bleed region if that region was capable of removing sufficient flow to create a new aerodynamic throat.

As the cowl is closed, the mass-flow ratio, $(m_2/m_o)|_{hs}$, decreases at the AIP. Inlet recovery also decreases. This reduction is probably due to both lower internal compression and proportionately greater ingestion of low momentum forebody boundary layer. Also, with some care, the 'popping' behavior can be discerned in the figure. Specifically, the cane curve with brown filled circle symbols shows an increase in recovery with back-pressure occurring with nearly constant flow for supercritical inlet operation. Then the bleed flow suddenly increases, with a decrease in m_2/m_0. 'Popping' also has hysteresis in that the terminal shock will not immediately 'pop' back. The details of the 'popping' behavior are discussed in more depth in the next section. The inlet did not unstart, but allowed a repositioning of the terminal shock within the inlet duct. Pressure recovery drops slightly (more evident on the higher capture flow /cowl position curves), and distortion increased slightly, (< 0.02, not shown). For normal shock control, this 'popping' behavior may present a significant complication, especially to the development of mode transition control procedures and schedules.

As the cowl is rotated down further, no unusual dynamics are observed even at the maximum reduction of low-speed flow capture for this configuration of the 1'x1' IMX model. This range of cowl rotation was from full open to 50% closed (approximately 5.7^0 out of the 11^0 full range of motion). Due to the decreases in both recovery and capture, the canes roughly follow lines of constant corrected airflow. An inlet mode transition schedule was manually simulated by manipulating the cowl angle and the low-speed cowl inlet mass-flow plug. This simulated mode transition process is indicated by the red curve with open circular symbols. Near the lowest flow, flow through the main mass-flow plug could then be reduced, mimicking turbine spool-down. Upon further screening of distortion levels, it was determined that the red curve may encounter some high distortions at the mass-flow ratios between 0.28 and 0.35, either from supercritical or 'popped' operation. A potentially better (lower distortion) mode transition schedule is indicated by the dotted black line labeled 'probable best mode transition schedule'. More refined engine face distortion measurements are needed to properly quantify distortion levels and limits. Due to the IMX test's small scale, industry standard 40-tube AIP distortion could not be incorporated. Never-the-less, the current study showed that Mach 4 performance is near the design goal and that smooth inlet mode transition can probably be achieved.

'POPPING' BEHAVIOR DETAILS

Ramp pressure distributions that illustrate a 'popping' behavior of the inlet are presented in figure 18. These data are for one of the cane curves that were presented in figure 17 as illustrated by the inset in the figure. The selected curve was for a low-speed cowl angle rotated toward closed, -2^0 from the design position. The curve was generated by back-pressuring the inlet from supercritical to inlet

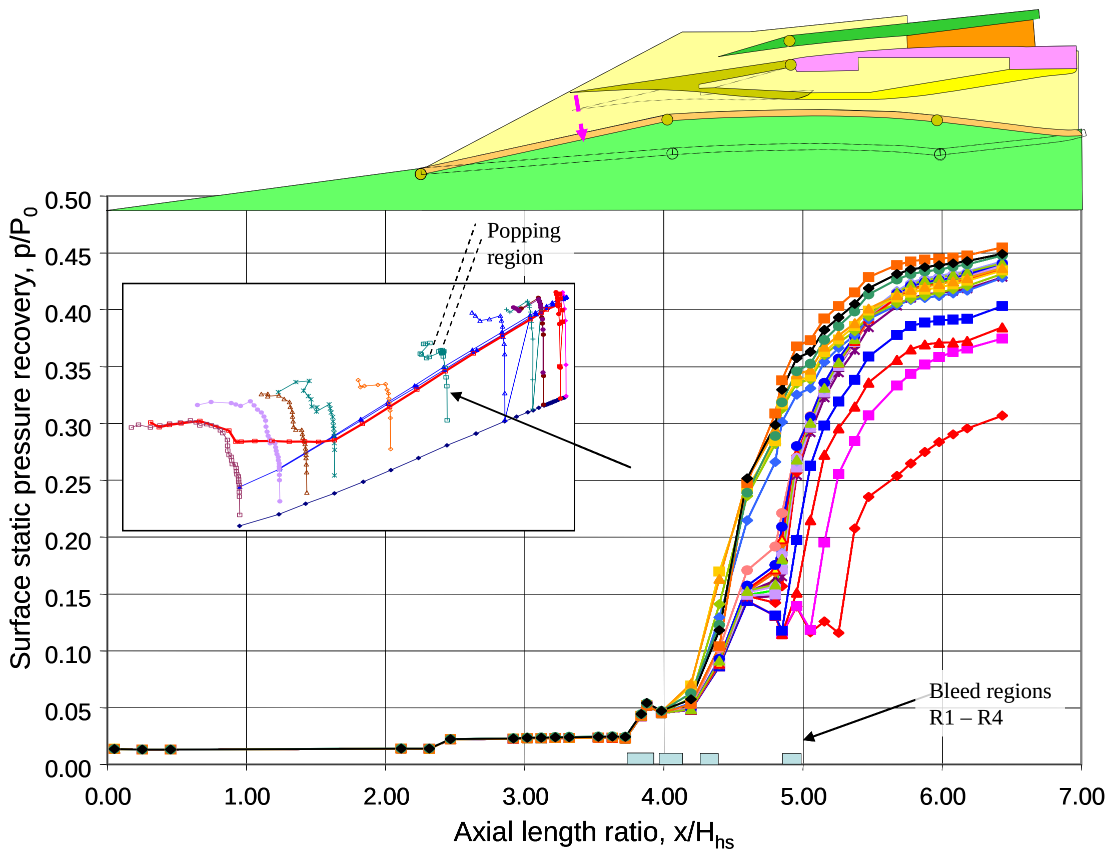


Figure 18: Low-speed inlet ramp pressure distributions for an inlet back-pressure trace at -2^o cowl lip rotation.

unstart/buzz conditions. Supercritical operation represented by the curve with the red diamond symbols, and the last back-pressured condition before buzz is represented by the curve with the black diamonds. Steady unstart data could not be obtained for the inlet when the cowl lip was set at the -2^0 position.

'Popping' can be seen in figure 18 by the shift in pressure distribution from the curve with the blue circular symbols to the pressure distribution represented by the curve with the blue diamonds. The blue circular symbol curve follows the supercritical pressure distribution to the inlet throat station where the normal shock pressure rise can be seen. This pressure rise begins at the ramp R4 bleed region. Referring to the curve with the blue diamond symbols, the pressure rise jumped forward to the bleed region R3 location. From this point, if the back-pressure was reduced (or engine corrected flow increased), the normal shock remains upstream on the R3 bleed. Thus the inlet 'popping' has hysteretic behavior.

OFF-DESIGN PERFORMANCE (MACH < 4.0)

In addition to the extensive testing to find a good Mach 4 bleed configuration, some off design performance was also screened during the testing. In figure 19, the IMX test results show near mil-spec performance over a range of Mach numbers. Data at Mach 3 and 4 are for design configurations. Data at Mach 2.5 and 3.5 were taken with the Mach 3 design geometries and are not truly representative of the performance of a design concept with full variable ramp geometry. The Mach 3 alternate mode transition geometries are termed VGC and VGR for Variable Geometry Cowl and Variable Geometry Ramp configurations, respectively. Note that the VGC configuration has better performance and warrants further study.

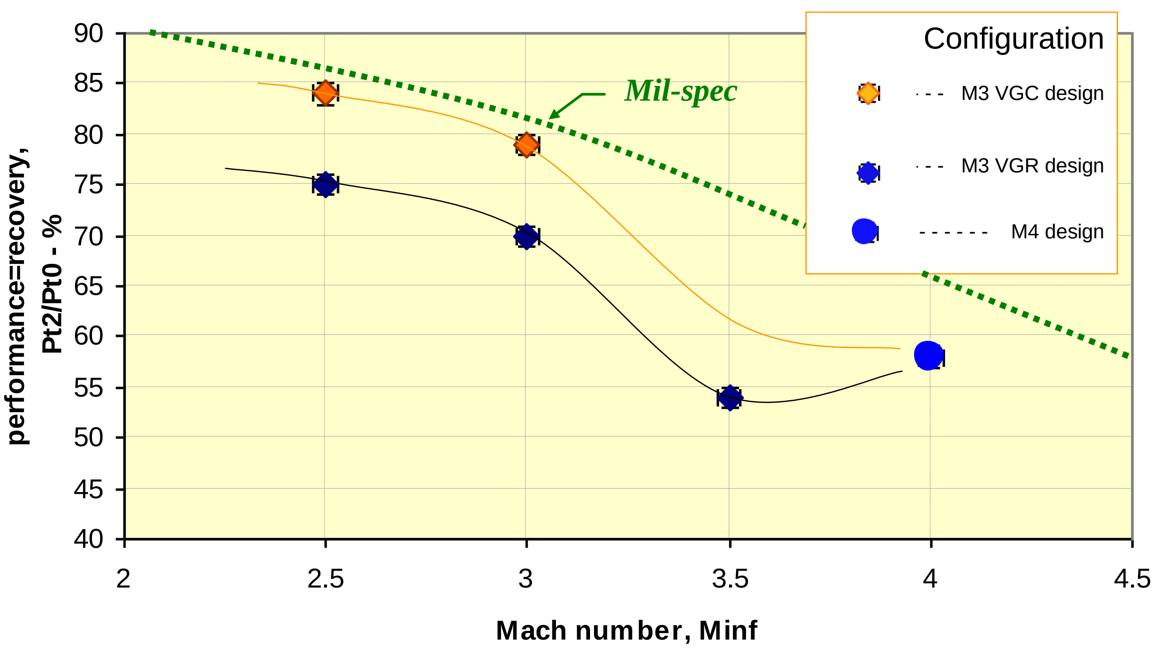


Figure 19: Off design performance: Inlet shows near mil-spec performance over a range of Mach numbers. Data at Mach 3 and 4 are for design configurations. Data at Mach 2.5 and 3.5 for Mach 3 design geometries.

IMX IMPACT ON CCE TESTBED

The screening effort completed to date with the small-scale IMX model test has lead to a set of requirements for a larger scale version of the inlet. These requirements are outlined in figure 20. In contrast to the small-scale model, the Large-scale Inlet Mode Transition (LIMX) model will be almost seven times larger and be able to test M3 turbofan and Dual-Mode Ram/Scramjet engines. The large 10'x10' SWT will accommodate the requirements for this CCET/LIMX project.

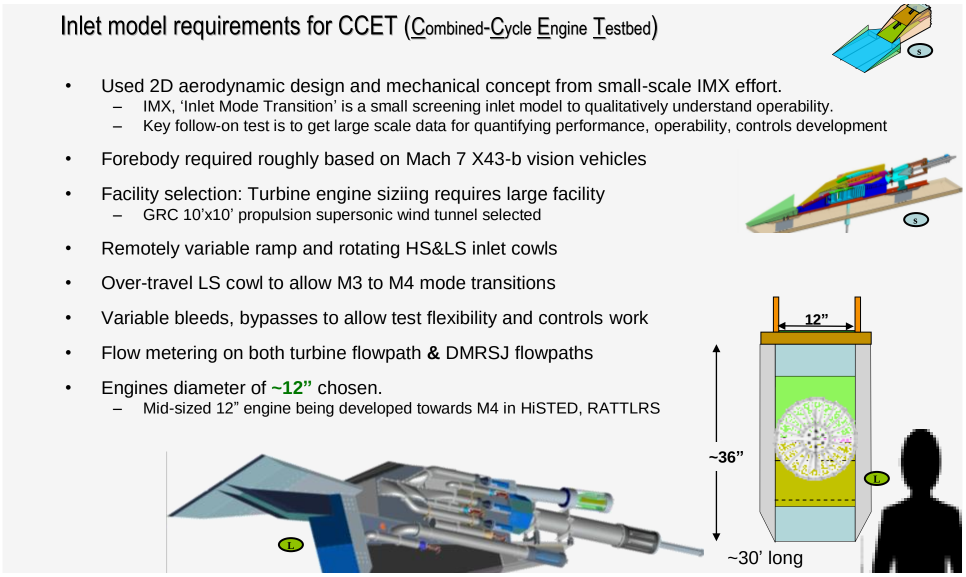


Figure 20: 1'x1' test of the IMX concept has confirmed a decision to invest resources into a large-scale version for the GRC 10'x10' SWT to obtain high quality data on mode transition performance and operability.

The overall effort is known as the Combined Cycle Engine Testbed project. Initially, the inlet will incorporate back-pressuring cold pipes to simulate the DMR/SJ and the turbine engines. The large-scale model will accommodate a larger set of inlet instrumentation needed to document performance, operability and dynamic transients during mode transition sequences. Full AIP instrumentation[25] will also document distortion characteristics for the turbine engine operation study. Small-scale IMX tests have provided needed confidence to develop larger CCET model based on the LIMX design.

SUMMARY OF RESULTS

Initial small-scale inlet testing and computational analysis has verified the aerodynamic design of a two-dimensional inlet system for an airbreathing, dual-mode, hypersonic propulsion system. The inlet design used in the test program included a low-speed Mach 4 inlet that was integrated into the flow path of a Mach 7 high-speed inlet. The low-speed inlet was designed to provide high performance airflow to the turbine engine from takeoff to Mach 4 flight conditions. At Mach 4, the low-speed inlet would close to allow operation of the high-speed propulsion system from Mach 4 to Mach 7. The inlet design included consideration of all of the normal subsystems required by traditional high-speed mixed-compression inlets. These systems include multiple bleed regions, a subsonic diffuser, overboard-bypass, controls, stability system(s), and vortex generators. Both the low-speed and high-speed inlets have variable geometry (rotating) cowl lip sections, and the low-speed inlet design included a variable geometry ramp (ramp at fixed positions for the small scale model). The inlet design effort resulted in an aerodynamic design that offers high performance and operability and is compatible with a realistic and practical variable geometry system. The inlet configuration developed in the design effort has been incorporated into the mechanical design and fabrication of two mode-transitioning research models -- small-scale (IMX) and large-scale (LIMX).

In a combined analytical/experimental approach, a TBCC Inlet design concept capable of smooth mode transition while maintaining high performance has been developed. Results from the small-scale screening test and the supporting CFD analyses proved the concept to be valid. Specific conclusions are:

- Inlet performance data obtained using the small-scale inlet model in the 1'x1' SWT have shown high performance with near mil-spec recovery at the transition Mach numbers as well as at off-design Mach numbers, (i.e. Mach 2.5 through 4).

- Test data indicate that smooth inlet mode transition is possible over a range of Mach numbers. Simulated mode transition was studied at Mach 4 and at Mach 3. A 'popping' hysteresis was observed at some conditions. This behavior may be reduced or eliminated by stability bleed or other control devices. This inlet design is sufficiently flexible to allow exploration of many mode transition scenarios.

- Preliminary results obtained through testing show that the design of the inlet might be further refined by changing contours to reduce the throat Mach number. This would enable higher performance and may have positive effects by reducing needed bleed flow and reducing engine face distortions.

- Inlet total pressure distortion effects require further investigations because it can have significant implications on the operability of the core engine. The current effort was not able to fully investigate distortion effects because of the small scale of the model, the limited instrumentation, and because vortex generator patterns could not be fully developed. In addition, viscous separation and vortex generator modeling are still research topics and have not been fully implemented into production CFD analysis.

- CFD is becoming a helpful tool in inlet design and continues to contribute in four areas: visualization of the flow field, validation of the design, instrumentation specification, and test planning. Bleed boundary condition models for analysis codes have been refined through application to this inlet design. Comparison to research data suggests that further model bleed refinements are needed.

These results give confidence that the LIMX inlet will perform as designed and also provide the flexibility needed for future CCET engine integrated systems testing.

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REFERENCES

1. Cassidy, M. D.: "Performance Sensitivities of a High Altitude Mach 5 Penetrator Aircraft Concept." NASA CR-3932, September 1985.
2. Perkins, E. W.; Rose, W. C.; and Horie, G.: "Design of a Mach 5 Inlet System Model. NASA CR-3830," August, 1984.
3. Weir, L.J.; and Sanders, B.W.: "Investigation of a Two-Dimensional, Mixed-Compression Mach 5.0 Inlet," NASA CR-2004-213122, July 2004.
4. Bradley, M.; Bowcutt, K., McComb, J.; Bartolotta, P.; and McNelis, N.: "Revolutionary Turbine Accelerator (RTA) Two-Stage-To-Orbit (TSTO) Vehicle Study," AIAA 2002-3902, July 2002.
5. Snyder, C.A.: "Thrust augmentation options for the Beta 2 two-stage-to-orbit vehicle," NASA-TM-106448; AIAA PAPER 93-4014, December, 1993.
6. Witte, D. W.; Hueber, L. D.; Trexler, C. A.; Cabell, K. F, and Andrews, E. H.: "Propulsion Airframe Integration Test Techniques for Hypersonic Airbreathing Configurations at NASA Langley Research Center," AIAA 2033-4406, July 2003.
7. Saunders, J. D.; Frate, F. C.; and Wendt, B. J.: "Inlet Design Methods for an X43B Demonstrator Vehicle," 27th JANNAF Airbreathing Subcommittee Meeting, December 2003.
8. See VAATE Web site at: http://www.pr.afrl.af.mil/divisions/prt/vaate/vaate.htm, or http://webext2.darpa.mil/tto/programs/hshr.htm, Last accessed on March 7, 2008.
9. See AFRL/Robust Scramjet Web site at: http://www.wpafb.af.mil/news/story.asp?id=123034952, Last accessed on March 7, 2008.
10. See ONR/RATTLRS Web link at: www.onr.navy.mil/media/extra/fact_sheets/rattlrs.pdf, File Format: PDF/Adobe Acrobat, Last accessed on March 7, 2008.
11. See DARPA/FALCON Web site at: http://www.darpa.gov/TTO/programs/Falcon.htm, Last accessed on March 7, 2008.
12. Trefny, C.J.; and Benson, T.J.: "An Integration of the Turbojet and Single-Throat Ramjet," NASA TM-107085, December 1995.
13. Fernandez, R.; Reddy, D.R.; Benson, T.J.; Iek, C.; Biesiadny, T.J.; and Wendt B.J.: "Design issues for turbine-based and rocket-based combined cycle propulsion system inlets," AIAA-1998-3774, July, 1998.
14. Davic, J.R.; Midea A.C.: Propulsion and Aerodynamic Analysis of the BETA II Two-Stage-to-Orbit Vehicle," AIAA-92-4245,
15. Burkardt, L.A.; Franciscus, L.C.: "RAMSCRAM: A flexible ramjet/scramjet engine simulation program," NASA-TM-102451, January, 1990.
16. Albertson, C. W.; Emami, S.; and Trexler, C. A.: "Mach 4 Test Results of a Dual-Flowpath, Turbine Based Combined Cycle Inlet," AIAA 2006-8138.
17. Sanders, B. W.; and Weir, L. J.: "Aerodynamic Design of a Dual-Flow Mach 7 Hypersonic Inlet System for a Turbine-Based Combined-Cycle Hypersonic Propulsion System," NASA-CR-2008-215214, June 2008.
18. Seablom, K.D.; Soeder, R.H.; Stark, D.E.; Leone, J.F.X.; Henry, M.W.: "NASA Glenn 1-by 1-Foot Supersonic Wind Tunnel User Manual," NASA/TM-1999-208478, April 1999.
19. Bush, R., Power, G., and Towne, C., "WIND: The Production Flow Solver of the NPARC Alliance," AIAA Paper 98-0935, 1998.
20. Nelson, C. C. and Power, G. D., "CHSSI Project CFD-7: The NPARC Alliance Flow Simulation System," AIAA Paper 2001-0594, 2001.
21. The Wind User's Guide, User Manual, The NPARC Alliance Web site at: http://www.grc.nasa.gov/WWW/winddocs/user/index.html.
22. Sanders, B. W.; and Mitchell, G. A.: "Throat-Bypass Bleed System for Increasing the Stable Airflow Range of a Mach 2.50 Axisymmetric Inlet with 40- Percent Internal Contraction," NASA-TM-X-2799, 1973.
23. Sanders, B. W.: "Dynamic Response of a Mach 2.5 Axisymmetric Inlet and Turbojet Engine with a Poppet-Valve Controlled Inlet Stability Bypass System when Subjected to Internal and External Airflow Transients," NASA TP-1531; 1980.
24. Slater, J. W.; and Saunders, J. D.: "Modeling of Fixed-Exit Porous Bleed Systems," AIAA–2008–0094, 2008.
25. Society of Automotive Engineers. "Gas Turbine Engine Inlet Flow Distortion Guidelines", Aerospace Recommended Practice (ARP) 1420, 1978.